# ENGINEERING DEVELOPMENT OF COAL-FIRED HIGH-PERFORMANCE POWER SYSTEMS

## DE-AC22-95PC95143

## TECHNICAL PROGRESS REPORT NO. 22
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## ABSTRACT

A High Performance Power System (HIPPS) is being developed. This system is a coal-fired, combined cycle plant with indirect heating of gas turbine air. Foster Wheeler Development Corporation and a team consisting of Foster Wheeler Energy Corporation, Bechtel Corporation, University of Tennessee Space Institute and Westinghouse Electric Corporation are developing this system. In Phase 1 of the project, a conceptual design of a commercial plant was developed. Technical and economic analyses indicated that the plant would meet the goals of the project which include a 47 percent efficiency (HHV) and a 10 percent lower cost of electricity than an equivalent size PC plant.

The concept uses a pyrolysis process to convert coal into fuel gas and char. The char is fired in a High Temperature Advanced Furnace (HITAF). The HITAF is a pulverized fuel-fired boiler/air heater where steam is generated and gas turbine air is indirectly heated. The fuel gas generated in the pyrolyzer is then used to heat the gas turbine air further before it enters the gas turbine.

The project is currently in Phase 2 which includes engineering analysis, laboratory testing and pilot plant testing. Research and development is being done on the HIPPS systems that are not commercial or being developed on other projects. Pilot plant testing of the pyrolyzer subsystem and the char combustion subsystem are being done separately.

This report addresses the areas of technical progress for this quarter. The detail of syngas cooler design is given in this report. The final construction work of the CFB pyrolyzer pilot plant has started during this quarter. No experimental testing was performed during this quarter. The proposed test matrix for the future CFB pyrolyzer tests is given in this report. Besides testing various fuels, bed temperature will be the primary test parameter.

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## EXECUTIVE SUMMARY

The High Performance Power System is a coal-fired, combined cycle power generating system that will have an efficiency of greater than 47 percent (HHV) with NOx and SOx less than 0.025 Kg/GJ (0.06 lb/MMBtu). This performance is achieved by combining a coal pyrolysis process with a High Temperature Advanced Furnace (HITAF). The pyrolysis process consists of a pressurized fluidized bed reactor which is operated at about 926°C (1700°F) at substoichiometric conditions. This process converts the coal into a low-Btu fuel gas and char. These products are then separated.

The char is fired in the HITAF where heat is transferred to the gas turbine compressed air and to the steam cycle. The HITAF is fired at atmospheric pressure with pulverized fuel burners. The combustion air is from the gas turbine exhaust stream. The fuel gas from the pyrolysis process is fired in a Multi-Annular Swirl Burner (MASB) where it further heats the gas turbine air leaving the HITAF. This type of system results in very high efficiency with coal as the only fuel.

We are currently in Phase 2 of the project. In Phase 1, a conceptual plant design was developed and analyzed both technically and economically. The design was found to meet the project goals. The purpose of the Phase 2 work is to develop the information needed to design a prototype/commercial plant. Phase 3 of the overall HIPPS contract has been deleted. In addition to engineering analysis and laboratory testing, the subsystems that are not commercial or being developed on other projects will be tested at pilot plant scale. The FWDC Second-Generation PFB pilot plant in Livingston, NJ, has been modified to test the pyrolyzer subsystem. The FWDC Combustion and Environmental Test Facility (CETF) in Dansville, NY, has been modified to test the char combustion system.

This report addresses the areas of technical progress for this quarter. One concern of hot gas cleaning systems utilized in HIPPS technologies is that some contaminants within the gas may pass through the particulate filter in the vapor form and cause corrosion and deposition problems in the downstream gas turbine. For coals, sodium and potassium are the principal elements causing concern. The only reliable and proven method today to capture these elements is to cool the gases enough to condense them onto ash particles and remove them via a particulate filter system. As a result, it was decided during the last quarter that a syngas cooler will be designed and be implemented for the future tests. The HIPPS syngas cooler is a four-pass, counter-flow single tube-in-tube heat exchanger design. The heat exchanger is a fire-tube design in which the pressurized syngas flows through an inner pipe and the cooling medium of pressurized superheated steam flows through an annulus consisting of a 4-inch outer pipe and the 3-inch inner pipe. The syngas is cooled from the partial gasifier exit temperature of 1950 °F to the desired filter inlet temperature in the range of 600 – 700 °F. This exit gas temperature range is desired to avoid possible tar formation in the filter and downstream equipment.

Metallic filters will be used for the syngas cleaning at the low temperature conditions. The CFB pyrolyzer tests will be conducted in two separate series. The first series of tests will be performed under the original configuration without the syngas cooler. The second series of tests will be performed under the new configuration with the syngas cooler and metallic filters. The first series of tests is aimed to study the CFB pyrolyzer operation and performance itself. The second series of test is aimed to study the performance of the CFB pyrolyzer and syngas filteration system.

Besides testing various fuels, bed temperature adjusted by the different air to fuel ratio will be the primary test parameter. Bed inventory and fluidization velocity will be the secondary test parameters. Fluidization velocity ranged from 12 ft/s to 15 ft/s will be tested. Steam injection into the pyrolyzer also will be tested. Two different fuel-feed locations will be tested.

## INTRODUCTION

In Phase 1 of the project, a conceptual design of a coal-fired high performance power system was developed, and small scale R&D was done in critical areas of the design. The current Phase of the project includes development through the pilot plant stage.

Foster Wheeler Development Corporation (FWDC) is leading a team of companies in this effort. These companies are:

- Foster Wheeler Energy Corporation (FWEC)
- Bechtel Corporation
- Westinghouse Electric Corporation

The power generating system being developed in this project will be an improvement over current coal-fired systems. Goals have been identified that relate to the efficiency, emissions, costs and general operation of the system. These goals are:

- Total station efficiency of at least 47 percent on a higher heating value basis.
- Emissions:

  NOx < 0.06 lb/MMBtu
  SOx < 0.06 lb/MMBtu
  Particulates < 0.003 lb/MMBtu

- All solid wastes must be benign with regard to disposal.
- Over 95 percent of the total heat input is ultimately from coal, with initial systems capable of using coal for at least 65 percent of the heat input.

The base case arrangement of the HIPPS cycle is shown in Figure 1. It is a combined cycle plant. This arrangement is referred to as the All Coal HIPPS because it does not require any other fuels for normal operation. A fluidized bed, air blown pyrolyzer converts coal into fuel gas and char. The char is fired in a high temperature advanced furnace (HITAF) which heats both air for a gas turbine and steam for a steam turbine. The air is heated up to 760$^{o}$C (1400$^{o}$F) in the HITAF, and the tube banks for heating the air are constructed of alloy tubes. The fuel gas from the pyrolyzer goes to a topping combustor where it is used to raise the air entering the gas turbine to 1288$^{o}$C (2350$^{o}$F). In addition to the HITAF, steam duty is achieved with a heat recovery steam generator (HRSG) in the gas turbine exhaust stream and economizers in the HITAF flue gas exhaust stream.

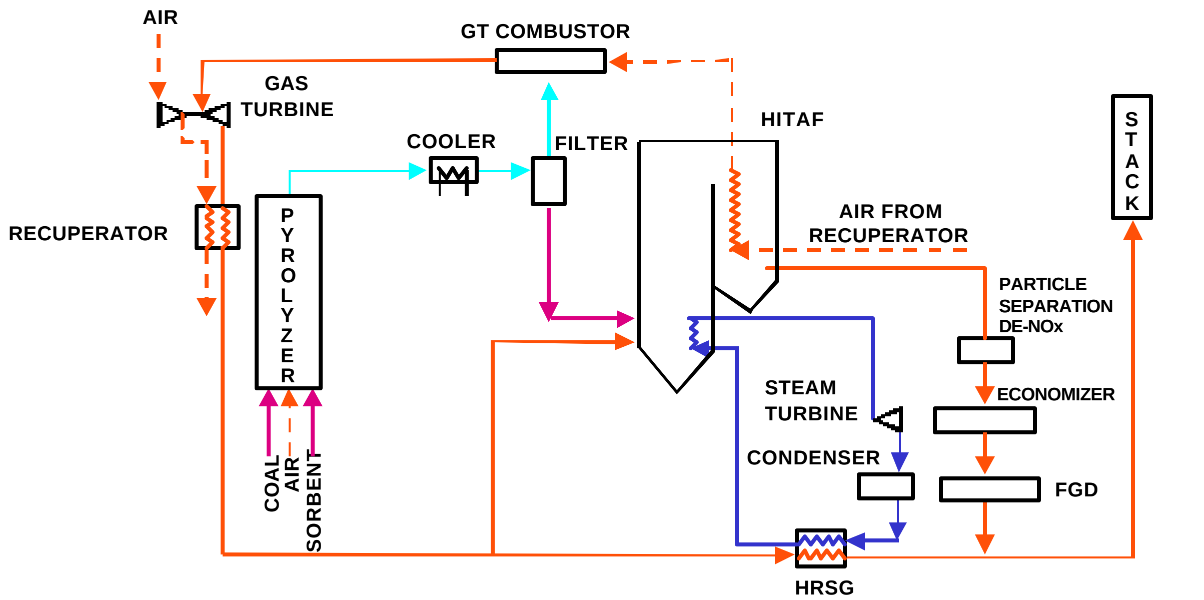


**Figure 1  All Coal Fired HIPPS**

An alternative HIPPS cycle is shown in Figure 2. This arrangement uses a ceramic air heater to heat the air to temperatures above what can be achieved with alloy tubes. This arrangement is referred to as the 35 percent natural gas HIPPS, and a schematic is shown in Figure 2. A pyrolyzer is used as in the base case HIPPS, but the fuel gas generated is fired upstream of the ceramic air heater instead of in the topping combustor. Gas turbine air is heated to 760°C (1400°F) in alloy tubes the same as in the All Coal HIPPS. This air then goes to the ceramic air heater where it is heated further before going to the topping combustor. The temperature of the air leaving the ceramic air heater will depend on technological developments in that component. An air exit temperature of 982°C (1800° F) will result in 35 percent of the heat input from natural gas.

A simplified version of the HIPPS arrangement can be applied to existing boilers. Figure 3 outlines the potential application of the HIPPS technology for repowering existing pulverized coal fired plants. In the repowering application, the gas turbine exhaust stream provides the oxidant for co-fired combustion of char and coal. The existing boiler and steam turbine infrastructure remain intact. The pyrolyzer, ceramic barrier filter, gas turbine, and gas turbine combustor are integrated with the existing boiler to improve overall plant efficiency and increase generating capacity.

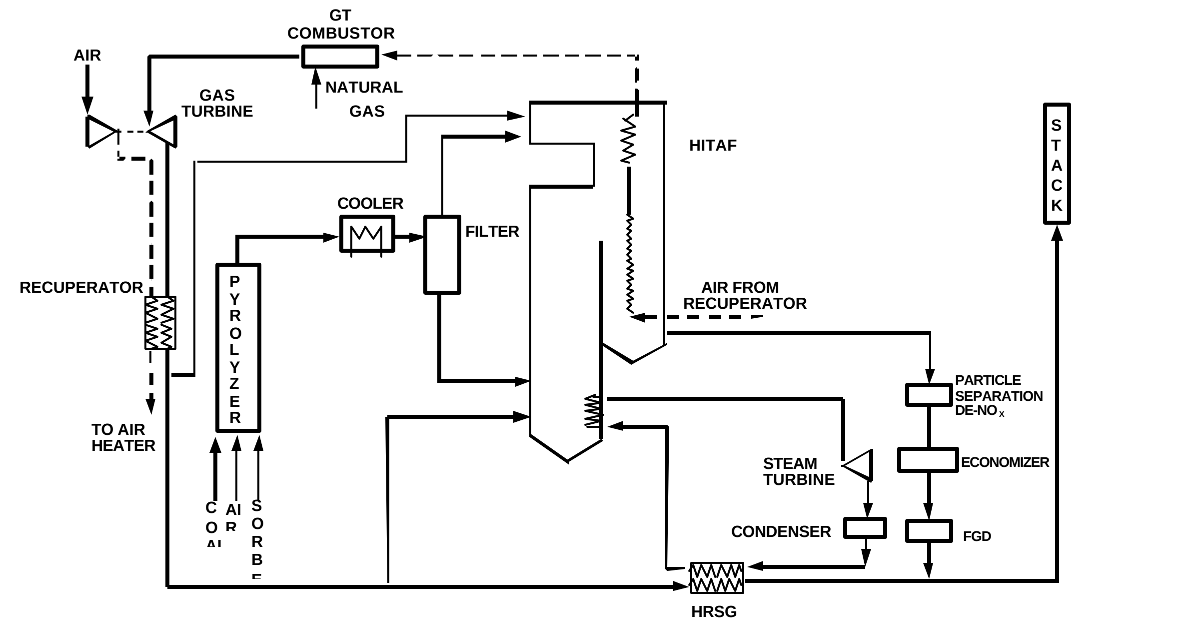


**Figure 2 35-Percent Natural Gas**

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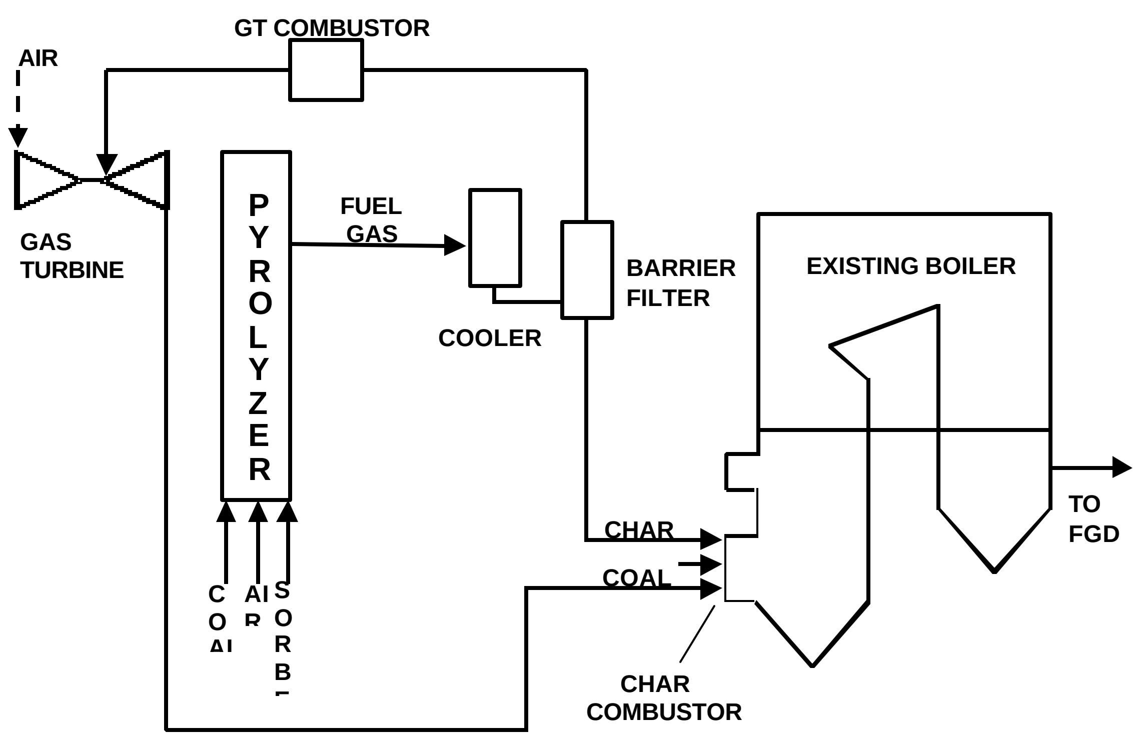



**Figure 3 Simplified HIPPS Repowering Process Flow Diagram**

## TECHNICAL PROGRESS

### Task 1 - Project Planning and Management

Work is progressing according to the project plan.

### Task 2 – Engineering Research and Development

No engineering R&D work was performed during this quarter.

### Task 3 - Subsystem Test Unit Design

### Subtask – 3.1 Livingston Pilot Plant Design

One concern of hot gas cleaning systems utilized in HIPPS technologies is that some contaminants within the gas may pass through the particulate filter in the vapor form and cause corrosion and deposition problems in the downstream gas turbine. For coals, sodium and potassium are the principal elements causing concern. For the HIPPS process, as the fuel is gasified in the pyrolyzer, the trace elements in the fuel are released and vaporized into the syngas. The only reliable and proven method today to capture these elements is to cool the gases enough to condense them onto ash particles and remove them via a particulate filter system. As a result, it was decided during the last quarter that a syngas cooler will be designed and be implemented for the future tests.

The HIPPS syngas cooler is a four-pass, counter-flow single tube-in-tube heat exchanger design with a total effective heat transfer length of 104 feet. The heat exchanger is a fire-tube design in which the pressurized syngas flows through an inner 3-inch sch. 80 pipe and the cooling medium of pressurized superheated steam flows through an annulus consisting of a 4-inch sch. 40 outer pipe and the 3-inch sch. 80 inner pipe. The syngas is cooled from the partial gasifier exit temperature of 1950 $^{o}$F to the desired filter inlet temperature in the range of 600 – 700 $^{o}$F. This exit gas temperature range is desired to avoid possible tar formation in the filter and downstream equipment.

The saturated steam from the existing facility boiler is used. This steam enters the heat exchanger counter-flow to the high temperature inlet syngas. After the first pass, water is injected to reduce the steam temperature. The resulting steam then passes counter-flow to the syngas for three additional passes. The steam attemperation allows lower metal temperatures at critical locations in addition to providing some control of the outlet syngas and metal temperature. Using steam as the cooling medium enables the minimum metal temperature of the syngas inner pipe to be maintained at approximately 500 - 550 ºF. City water is used to desuperheat the steam. A schematic arrangement of the cooling circuit and the P&ID are presented in Figures 4 and 5. Figure 6 shows details of the syngas cooler general arrangement. The cooler is instrumented at certain locations for performance evaluations.

Metallic filters will be used for the syngas cleaning at the low temperature conditions. The CFB pyrolyzer tests will be conducted in two separate series. The first series of tests will be performed under the original configuration without the syngas cooler. The second series of tests will be performed under the new configuration with the syngas cooler and metallic filters. The first series of tests is aimed to study the CFB pyrolyzer operation and performance itself. The second series of test is aimed to study the performance of the CFB pyrolyzer and syngas filteration system.

**Subtask – 3.2 Char Combustion System Test Design**

No design work was performed during this quarter.

**Task 4 - Subsystem Test Unit Construction**

**Subtask – 4.1 Livingston Pilot Plant Construction**

During this quarter, the final construction work of the CFB pyrolyzer pilot plant has started. The pyrolyzer refractory has been modified to a constant 7-inch diameter throughout the reactor. The new cyclone and solids return leg were received and installed. The new frame arrestors were received and installed. The calibration of the new frame arrestors will be performed in January 2001 by the vendor. Backend pressure control valve, which includes the fixed flow orifice and syngas bypass cooler, was modified. The diameter of the fixed flow orifice was increased to accommodate the increased syngas flow in the CFB mode. A new fuel feed port located on the side of the CFB pyrolyzer was installed.

To make the char transfer from the Livingston, NJ facility to the Dansville, NY facility easier, an arrangement with a regional tanker and transportation company has been made. A rental tanker will be used to store most of the char produced during the test. In the original configuration, after depressurization in the lock hopper system, the char is dense phase transported into an outside baghouse. Then, char is discharged into drums for storage. In the new configuration, the char will be dense phase transported into the rental tanker. After the test, the tanker will be transferred to the Dansivlle, NY facility for the char combustion test.

Arrangements have been made to conduct the New Jersey Department of Environmental Protection stack compliance test during the first test run.

**Subtask – 4.2 Char Combustion System Construction**

No Construction work was performed during this quarter.

**Task 5 - Subsystem Test Unit Testing**

**Subtask – 5.1 Livingston Pilot Plant Testing**

No experimental testing was performed during this quarter. The overall construction and testing schedule for the CFB pyrolyzer test is shown in Figure 7. HIPPS testing on CFB pyrolyzer can begin as early as February 2001.

As mentioned in the earlier report, CFB pyrolyzer tests will be performed in two series. The first to be tested will be a CFB pyrolyzer with a high temperature (1500-1950 $^{o}$F) filteration system. After the first testing is completed, the syngas cooler will be added to the pilot plant and ceramic filters will be replaced with metallic filters. Table 1 shows the proposed test matrix. Besides testing various fuels, bed temperature adjusted by the different air to fuel ratio will be the primary test parameter. Bed inventory and fluidization velocity will be the secondary test parameters. Fluidization velocity ranged from 12 ft/s to 15 ft/s will be tested. Steam injection into the pyrolyzer also will be tested. Two different fuel-feed locations will be tested. Typical heat and material balances for the pilot plant are provided in Figures 8 and 9. These balances are based upon the use of Wyoming Eagle Butte coal, and assume a 1% heat loss to the surroundings.

**Subtask – 5.2 Char Combustion System Testing**

No experimental testing was performed during this quarter. The char combustion test will be aligned with the CFB pyrolyzer test. All the char produced by the CFB pyrolyzer will be combusted at the CETF. Based on the current progress, char combustion test is scheduled to commence in May and July 2001.

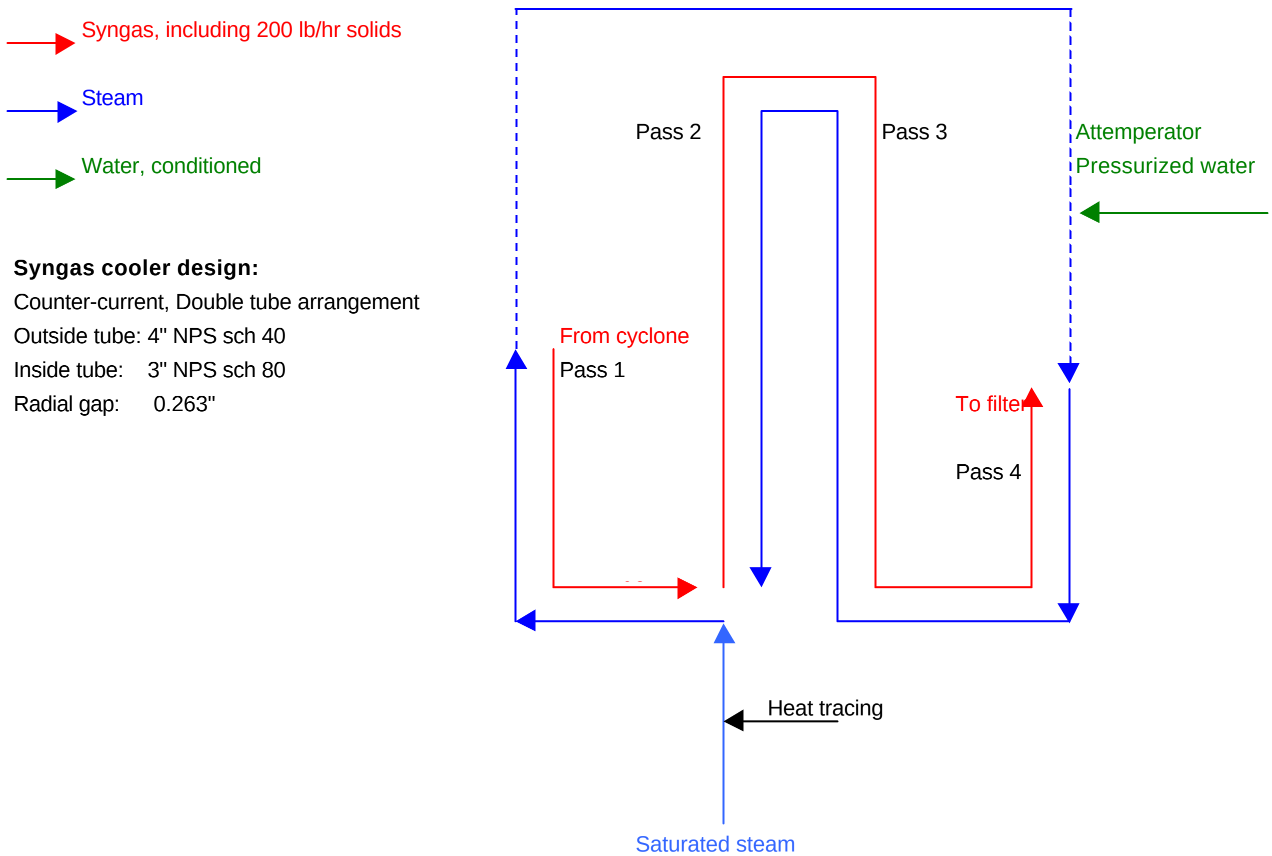
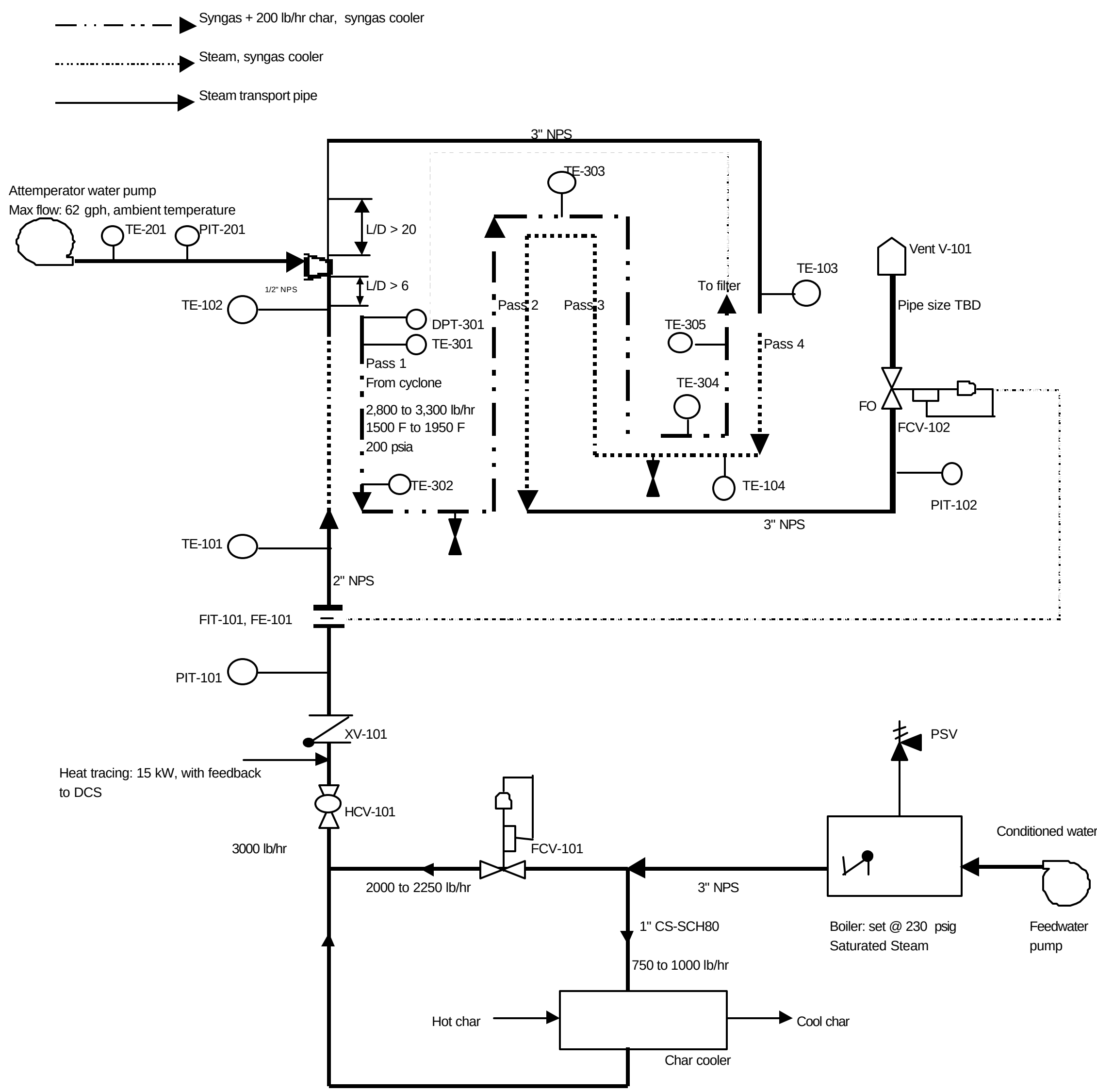



**Figure 4 HIPPS Syngas Cooler Cooling Circuit**




Notes:
1) Pass 1 and Pass 4 of the syngas cooler are to be insulated
2) Steam transport lines prior to syngas cooler are to be insulated
3) Drains are to be provided at low points
4) Sufficient L/D should be provided after the two different temperature steam streams and heat tracing to insure adequate steam mixture temperature entering syngas cooler
5) Temperature elements (TE), FITs, PITs, and attemperator water temperature/flow output to be wired to DCS
6) Syngas flow to be measured at some point in the system
7) Piping after the flow control valve should be straight run
8) Pipe size after the flow control valve is dependent on noise abatement equipment
9) Differential pressure measurement between inlet and outlet of syngas cooler
10) Vendor to confirm local pipe size of flow control valve and orifice

**Figure 5 P&ID for HIPPS Syngas Cooler Arrangement**

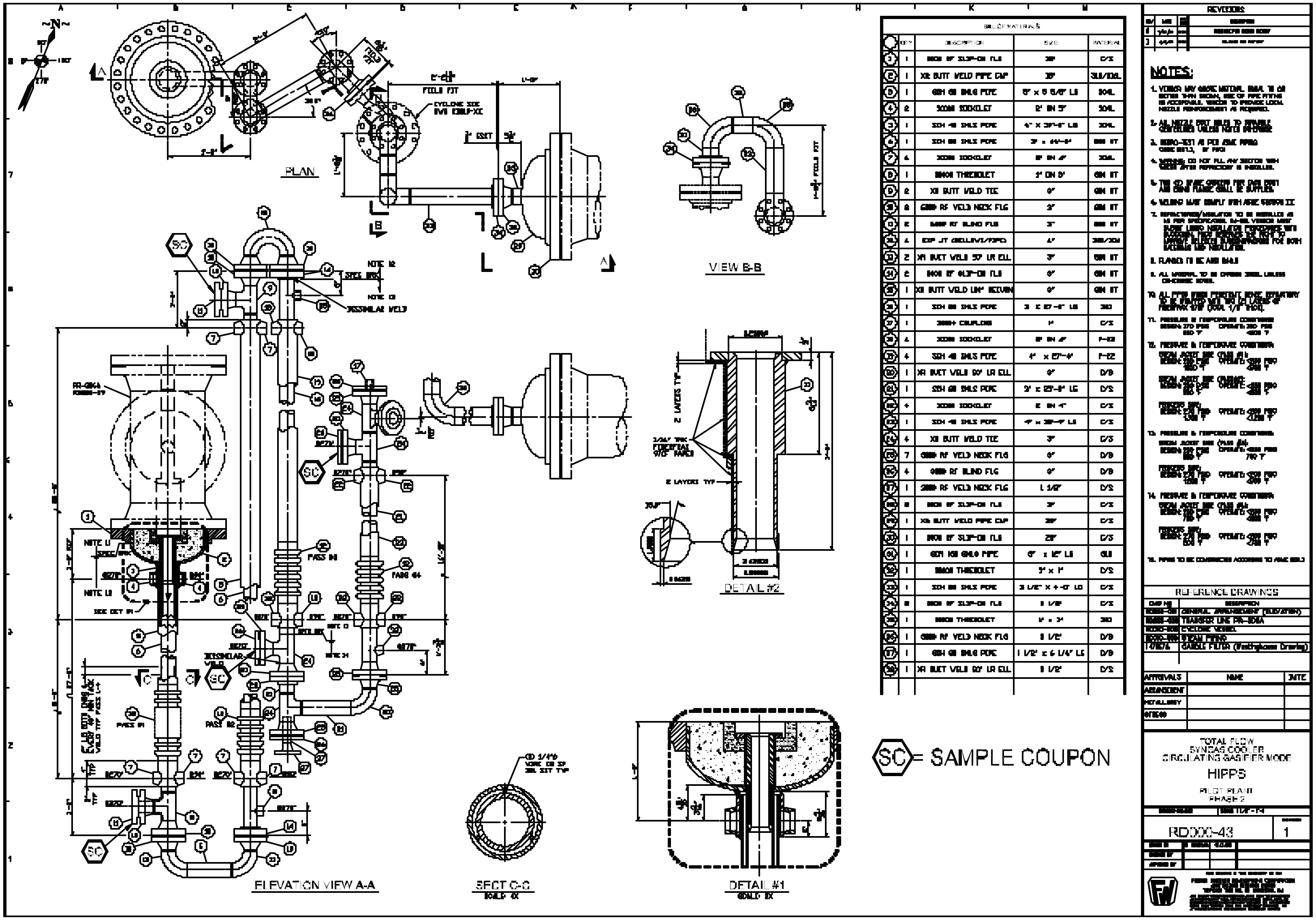



Figure 6  Syngas Cooler Arrangement

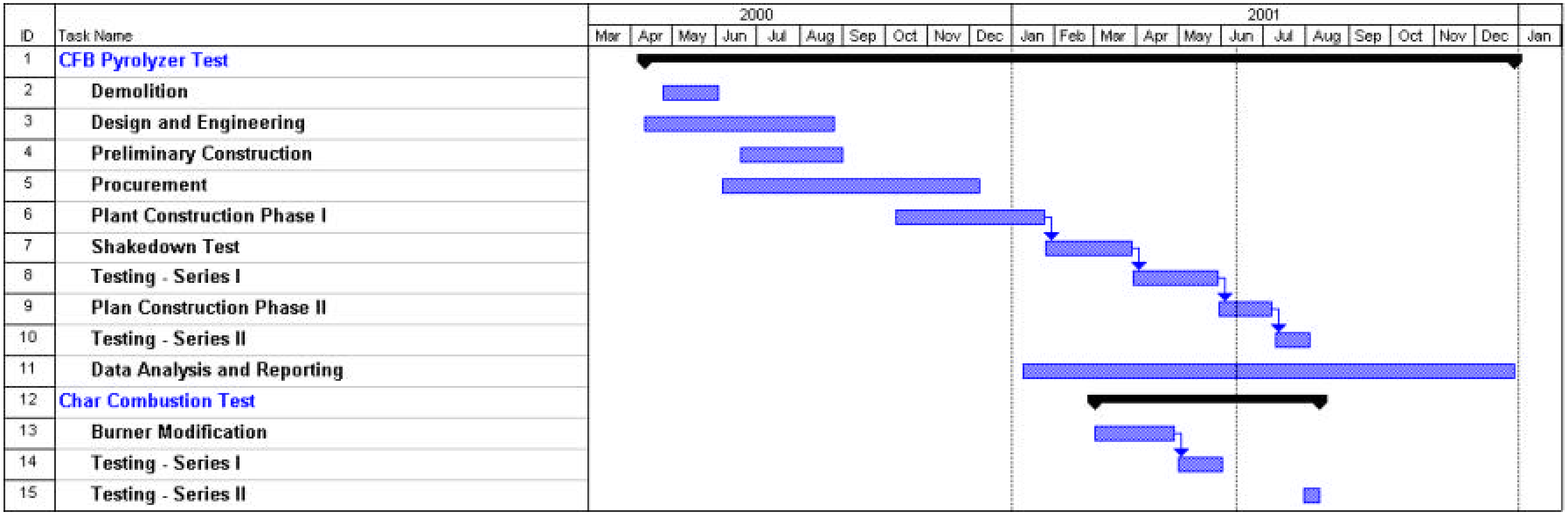



**Figure 7 Overall CFB Pyrolyzer System Construction and Testing Schedule**

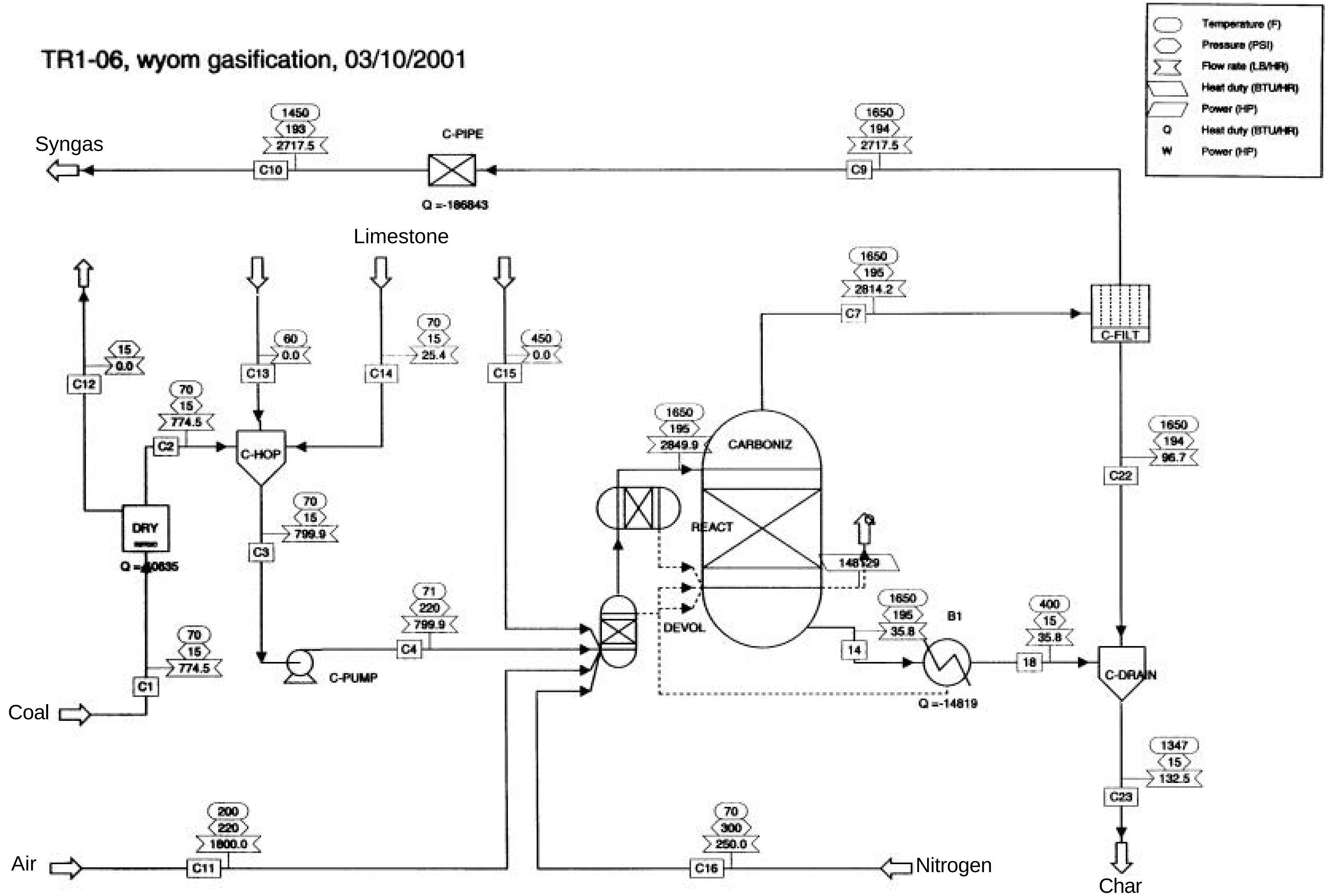
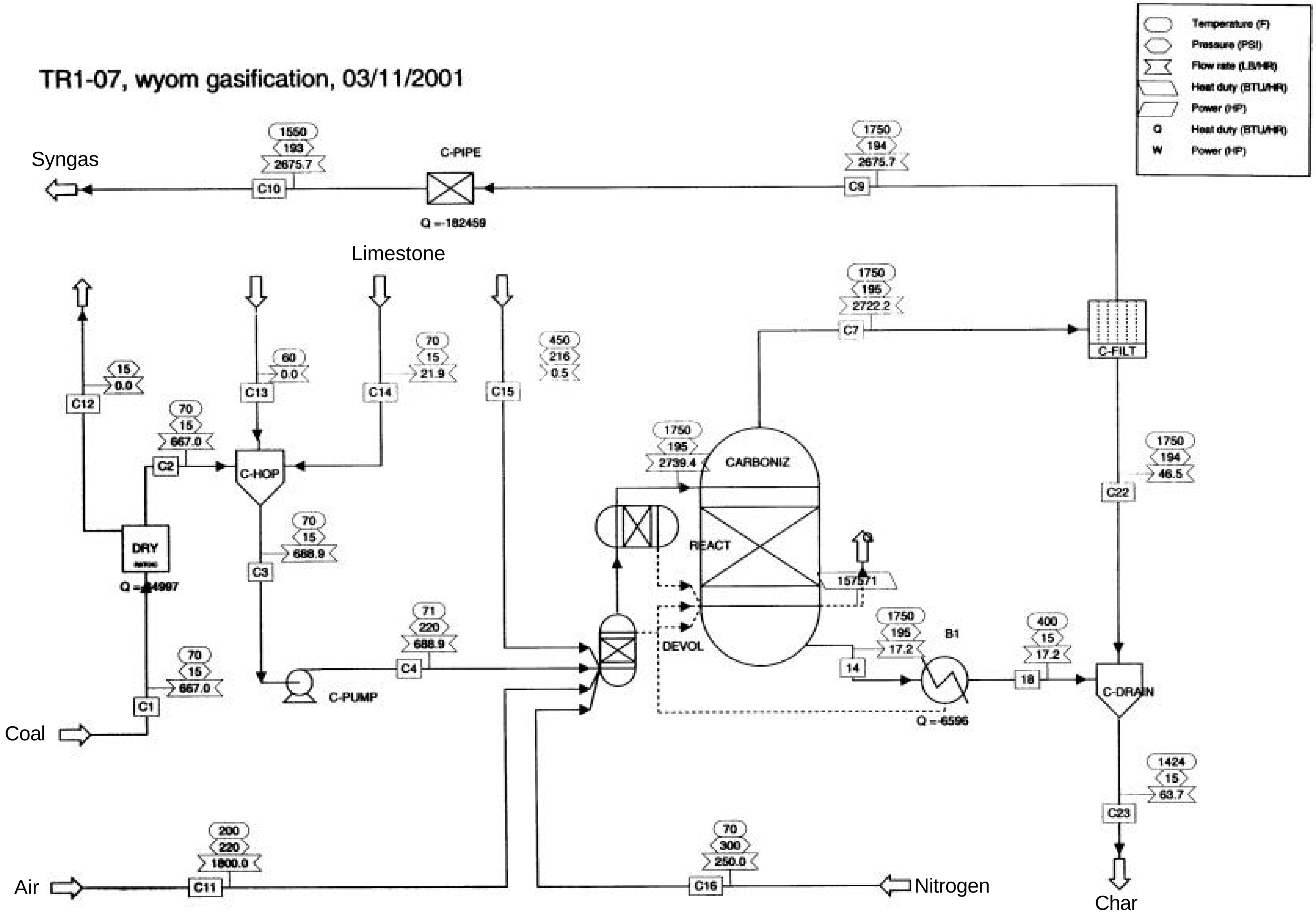

TR1-06, wyom gasification, 03/10/2001
Temperature (F)
Pressure (PSI)
Flow rate (LB/HR)
Heat duty (BTU/HR)
Power (HP)
Q Heat duty (BTU/HR)
W Power (HP)
Syngas
1450
193
2717.5
C10
C-PIPE
Q =-186843
1650
194
2717.5
C9
Limestone
1650
195
2814.2
C7
C-FILT
15
0.0
C12
60
0.0
C13
70
15
25.4
C14
450
0.0
C15
70
15
774.5
C2
C-HOP
70
15
799.9
C3
DRY
1650
195
2849.9
CARBONIZ
REACT
148129
1650
194
96.7
C22
71
220
799.9
C4
C-PUMP
DEVOL
1650
195
35.8
14
B1
Q =-14819
400
15
35.8
18
C-DRAIN
70
15
774.5
C1
Coal
1347
15
132.5
C23
200
220
1800.0
C11
Air
70
300
250.0
C16
Nitrogen
Char

**Figure 8 Typical Pyrolyzer Mass and Energy Balance for 1650 $^{o}$F Temperature**



TR1-07, wyom gasification, 03/11/2001
Temperature (F)
Pressure (PSI)
Flow rate (LB/HR)
Heat duty (BTU/HR)
Power (HP)
Q Heat duty (BTU/HR)
W Power (HP)
Syngas
C-PIPE
Q = -182459
Limestone
C-FILT
CARBONIZ
REACT
DEVOL
B1
Q = -6596
C-DRAIN
C-HOP
DRY
C-PUMP
Coal
Air
Nitrogen
Char
C1
C2
C3
C4
C7
C9
C10
C11
C12
C13
C14
C15
C16
C22
C23
14
18
157571
1550
193
2675.7
1750
194
2675.7
1750
195
2722.2
1750
195
2739.4
1750
194
46.5
15
0.0
60
0.0
70
15
21.9
450
216
0.5
70
15
667.0
70
15
688.9
71
220
688.9
70
15
667.0
1750
195
17.2
400
15
17.2
1424
15
63.7
200
220
1800.0
70
300
250.0

**Figure 9 Typical Pyrolyzer Mass and Energy Balance for 1750 $^{o}$F Temperature**

**Table 1  HIPPS CFB Pyrolyzer Test Matrix**

| Test Series | Test # | Fuel | Riser Velocity (FPS) | Pressure (PSIA) | Temperature ($^oF$) | Bed Inventory (IN. WC.) | Steam Injection | Sand | Syngas Cooler | Filters |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | Wyoming Eagle Butte Coal | 12 | 200 | 1550 | 90 | No | Yes | No | Ceramic |
| 1 | 2 | Wyoming Eagle Butte Coal | 12 | 200 | 1650 | 90 | No | Yes | No | Ceramic |
| 1 | 3 | Wyoming Eagle Butte Coal | 12 | 200 | 1750 | 90 | No | Yes | No | Ceramic |
| 1 | 4 | Colorado West Elk Coal | 12 | 200 | 1650 | 90 | No | Yes | No | Ceramic |
| 1 | 5 | Colorado West Elk Coal | 12 | 200 | 1750 | 90 | No | Yes | No | Ceramic |
| 1 | 6 | Colorado West Elk Coal | 12 | 200 | 1850 | 90 | No | Yes | No | Ceramic |
| 1 | 7 | Colorado West Elk Coal | 12 | 200 | 1850 | 90 | Yes | Yes | No | Ceramic |
| 1 | 8 | Colorado West Elk Coal | 12 | 200 | 1950 | 90 | Yes | Yes | No | Ceramic |
| 2 | 1 | Colorado West Elk Coal | 12 | 200 | 1850 | 90 | Yes | Yes | Yes | Metallic |
| 2 | 2 | Colorado West Elk Coal | 12 | 200 | 1850 | 120 | Yes | Yes | Yes | Metallic |
| 2 | 3 | Colorado West Elk Coal | 15 | 200 | 1850 | 90 | Yes | Yes | Yes | Metallic |
| 2 | 4 | Colorado West Elk Coal | 15 | 200 | 1850 | 120 | Yes | Yes | Yes | Metallic |
| 2 | 5 | Colorado West Elk Coal | TBD | 200 | 1950 | TBD | TBD | Yes | Yes | Metallic |
| 2 | 6 | TBD | TBD | 200 | TBD | TBD | TBD | Yes | Yes | Metallic |
| 2 | 7 | TBD | TBD | 200 | TBD | TBD | TBD | Yes | Yes | Metallic |
| 2 | 8 | TBD | TBD | 200 | TBD | TBD | TBD | Yes | Yes | Metallic |
| 2 | 9 | TBD | TBD | 200 | TBD | TBD | TBD | Yes | Yes | Metallic |
| 2 | 10 | TBD | TBD | 200 | TBD | TBD | TBD | Yes | Yes | Metallic |